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The Initiation and Growth of Intergranularly Initiated Short Fatigue Cracks in an Aluminium 4.5 per cent Copper Alloy

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ABSTRACT The initiation and growth of short fatigue cracks with surface length in the range 60–1000 μm in a peak aged Al 4.5 wt% Cu alloy with a grain size of 200–400 μm has been studied. Testing was carried out on small plane specimens in three point bend at stress levels below that for gross yield. Observations were made using cellulose acetate replication techniques and a miniature bending rig for use in the scanning electron microscope (SEM).

In all cases crack initiation occurred at grain boundaries. Transmission electron microscope (TEM) examination of the boundaries revealed the presence of the equilibrium θ precipitates and an accompanying precipitate-free zone.

Surface growth of grain boundary cracks was observed to be retarded at inclusions, grain boundary triple points, and positions of transition from intergranular to transgranular growth.

Introduction

In the studies of short fatigue crack propagation in aluminium alloys most of the experimental work has been done on either machined-down long pre-cracks or on contained cracks initiated at intermetallic particles either by cracking of the particle itself or cracking of the particle–matrix interface (**1**)(**2**). However, these particle initiation mechanisms are not the only ones known to occur in aluminium alloys. The other mechanisms are either associated with persistent slip bands or grain boundaries.

Initiation of fatigue cracks at grain boundaries in single phase materials can take place even though the boundaries themselves are not inherently weak. This occurs by the so called 'geometric rumpling' mechanism and is due to severe deformation within the grains causing what are effectively micro-notches along the boundaries and subsequent crack initiation (**3**).

In multi-component materials the situation is complicated by the occurrence of segregation. This paper examines the initiation and growth of cracks in a precipitation hardening system which has a number of special segregation problems associated with it.

After initiation the growth of short cracks has been found to be affected by grain boundaries in a number of materials and at second phase boundaries, particularly in steels (**4**). This work looks at another aspect of short crack growth where the growth mechanism changes from intergranular to transgranular.

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Material and test methods

The Al, 4.5% Cu alloy had a yield stress of 258 MPa, a tensile strength of 340 MPa, and an elongation of 26 per cent.

The material was made from high purity base metals in the laboratory. Solution treatment was carried out at the relatively low temperatures of 500°C to ensure that any furnace temperature fluctuations did not result in localized grain boundary melting. Between solution treatment and ageing no additional deformation was given. An ageing curve was then determined for the material at 160°C. The alloy was aged for 16 hours to obtain peak hardness.

Fatigue testing was carried out using a small three point bend rig, using plain rectangular specimens of dimensions 6 × 15 × 32 mm, on an Amsler vibrophore at a frequency of approximately 100 Hz. The maximum tensile stress at the surface of the specimen is given by the equation

$$\sigma_{\max} = \frac{3PL}{2Bw^2} \tag{1}$$

where

P = applied load
L = length between upper loading points (24 mm)
B = width of specimens (15 mm)
w = thickness of specimen (6 mm)

All tests were carried out at surface stress levels below the tensile yield stress at an R ratio of 0.15. Specimens were polished to a 6 μm finish then electropolished in a 3 per cent perchloric acid, 32 per cent butoxyethanol, 65 per cent methanol solution at −50°C with an open circuit voltage of 60 V for five minutes in an effort to remove any residual stresses resulting from machining.

Crack detection and growth measurements were made using cellulose acetate replicas which were examined at ×400 magnification using a light microscope with a vernier eyepiece. Using this method crack length changes down to 1 μm could be detected, although at least 5 μm growth or 10^6 cycles were generally allowed between measuring increments.

For further detailed examination replicas were sputtered with gold and then plated with copper from a copper sulphate solution. The metal was then stripped from the plastic to give a positive replica of the specimen surface which could be examined in the scanning electron microscope. In addition to this method an *in situ* three point bend rig was made to enable specimens to be deflected in the electron microscope. The loading dimensions of the *in situ* rig were the same as those of the rig on the fatigue testing machine and the loadings were calibrated directly using a strain gauge on each specimen.

In view of the initiation mechanism which was observed a number of TEM foils were thinned using twin electro-jet polishing at −30°C with a closed circuit voltage of 14 V in a 30 per cent nitric acid in methanol solution. The foils were then examined in a Philips EM 400 scanning transmission electron microscope.

Results and discussion

It was observed in more than 30 specimens that crack initiation invariably took place at grain boundaries. The initiation event, that is, the number of cycles after which a crack could be unmistakably observed at lengths of around 50 μm, occurred after approximately 10^5 cycles at a maximum stress of 80 per cent of the tensile yield stress.

The result of the TEM examination of the material is shown in Fig. 1. The micrograph shows the area around a grain boundary. It can be seen that along the boundary there were a number of elongated θ precipitates surrounded by a light area, the precipitate-free zone, with the remainder of the material being made up of the θ'' and θ' precipitates associated with peak hardness in the matrix.

The reasons for the occurrence of precipitate-free zones are now well established and are essentially bound up with the fact that the boundaries are low strain and surface energy sites for precipitation and sinks for vacancies (**5**).

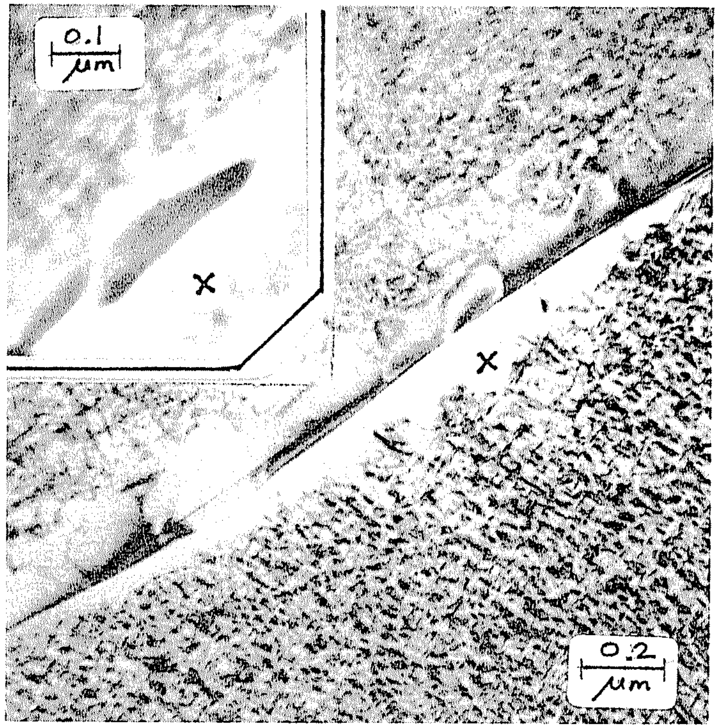

Fig 1 Transmission electron microscope micrographs of the experimental material showing θ precipitates (x) lying in a grain boundary precipitate free zone

In later experiments on an alloy of 0.5 per cent lower copper content, fatigue testing in the solution-treated and quenched condition produced extensive persistent slip band formation with no grain boundary cracking. When subsequently peak aged and re-tested, initiation took place at large intermetallic intragranular inclusions in the more usual way. This result would tend to confirm the conclusion that in the peak aged alloy the precipitate-free zones rather than any stray embrittling impurities cause crack initiation since the presence of any impurities on the boundaries would be just as likely in the solution-treated as in the aged condition. Fatigue testing in the solution-treated condition produced plastic strains within the grains creating additional vacancies and favourable sites for intragranular precipitation thereby making precipitation on the boundaries and the formation of associated precipitate-free zones less likely.

The crack propagation data has been presented in terms of both log c, where c is the half surface crack length from tip to tip, and log ΔK, where, for a semi-circular surface crack, $K = 0.8847\ \sigma\sqrt{(\pi c)}$ (6). Neither parameter is entirely satisfactory for a number of reasons (7) but both are useful in comparing cracks of a similar length in the same material.

Figure 2(a) shows growth rate data for a crack growing in the initiating grain boundary. It was found that, when uninterrupted by microstructural features, the crack growth rate increased with increasing crack length, as would be expected.

Figure 2(b) shows data for a crack which grew along the initiating boundary, section A, until it encountered a triple point at B. At this point the crack growth was retarded until continued growth took place in a transgranular manner at C after a 6 per cent increase in stress range. This type of retardation at triple points was observed a number of times. The reason for this behviour is unclear, but it is perhaps useful to regard the material as being made up of what are essentially two 'regions': the first being a soft grain boundary region of a dilute aluminium copper solid solution, and the second being the harder matrix region of the precipitation-hardened material. Hence, for crack growth at the same rate, the crack length or ΔK required would be higher in the matrix region than in the grain boundary. This explanation is similar to that put forward by de Los Rios *et al.* (4) for growth of cracks along prior austenite grain boundaries in a steel.

Alternatively the problem may be seen as similar to the grain boundary retardations reported by other workers (8) for entirely transgranular cracks. This explanation requires that a crack builds up plasticity and reorientates itself for growth in the next grain.

Although growth mechanism changes took place at triple points in an approximately equal number of cases the growth mechanism remained unchanged at the first triple point. This continued intergranular growth could also result in growth rate changes which were due to two factors. Since the crack lengths are measured normal to the stress axis any increased deviation from this

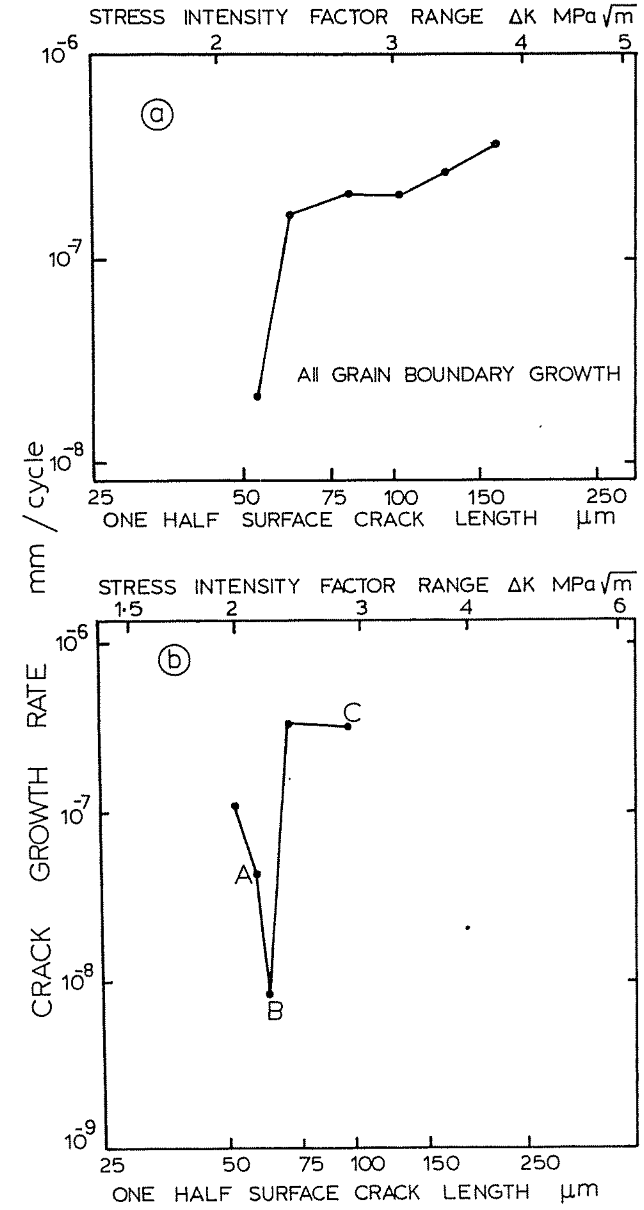

Fig 2 Fatigue crack propagation data.
(a) An uninterrupted crack growing in the initiating boundary
(b) A grain boundary crack (A) retarded at a triple point (B). Transgranular growth took place at (c) after a 6 per cent increase in stress

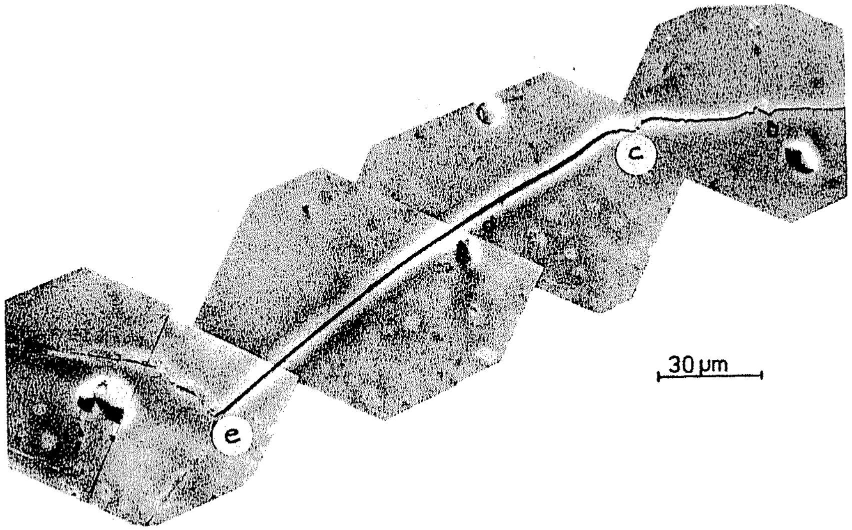

Fig 3 Fatigue crack growth showing both transgranular and intergranular growth from triple points (c) and (e), respectively. The photograph was taken at maximum load in the *in situ* rig and the tensile stress axis is vertical

direction results in an apparent decrease in growth rate. (Conversely, any decreased deviation will result in an apparent increase in growth rate). Hence, for individual cracks, apparent propagation rates may change markedly. Again, associated with deviation of the crack growth direction from the stress axis normal is the mechanism of crack deflection described by Suresh (9), where the change in crack plane results in an overall reduction in the stress intensity range and a real growth-rate reduction.

An example of a crack showing both types of triple point behaviour is shown in Fig. 3.

Figure 4 shows a number of examples of short crack behaviour. The data in the centre is for a crack which was retarded (A) at an inclusion on the initiating boundary, a replica of which is shown in Fig. 5. The surface length, $2c$, of this crack was 95 μm and the inclusion was 9.5 μm in diameter. It has been observed that only inclusions of a size greater than 5 μm had any effect on propagation rates, and the maximum length of crack for which any significant interactions with microstructure took place was 500 μm.

The retardation of grain boundary cracks at surface inclusions may be due to prevention of slip at the crack tip. Since any inclusion will only occupy a small fraction of the crack front – in the case described about 3 per cent if it is assumed to be spherical – then it could be argued that the important slip for growth takes place close to the surface of the specimen. However, it may also be possible that any inclusion of a reasonable size on a crack front of this length would cause an arrest or retardation. If this is so it would tend to indicate that at short crack lengths the difference between growth and non-growth is only marginal.

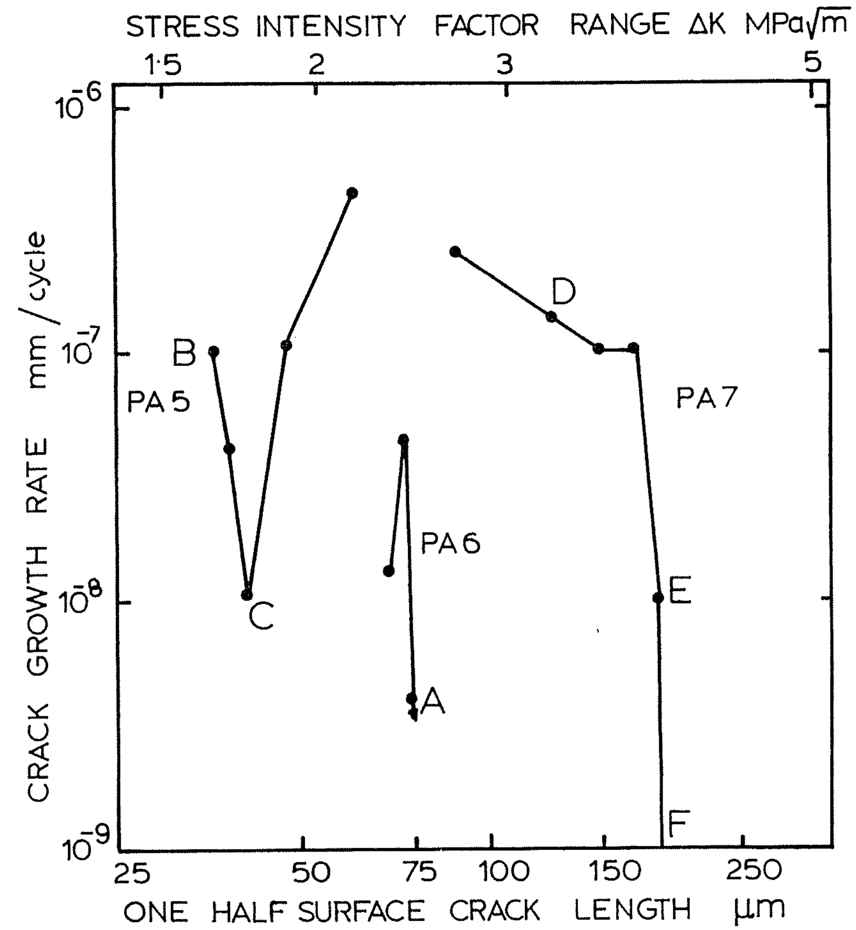

Fig 4 Propagation data for three cracks in samples PA5, PA6, and PA7.

A	**one crack tip at an inclusion the other tip at a grain boundary triple point**
B and D	**grain boundary growth**
C	**crack branching**
E	**one crack tip growing transgranularly and the other tip growing intergranularly**
F	**transgranular crack tip arrested near grain boundary, the other tip arrested in the boundary**

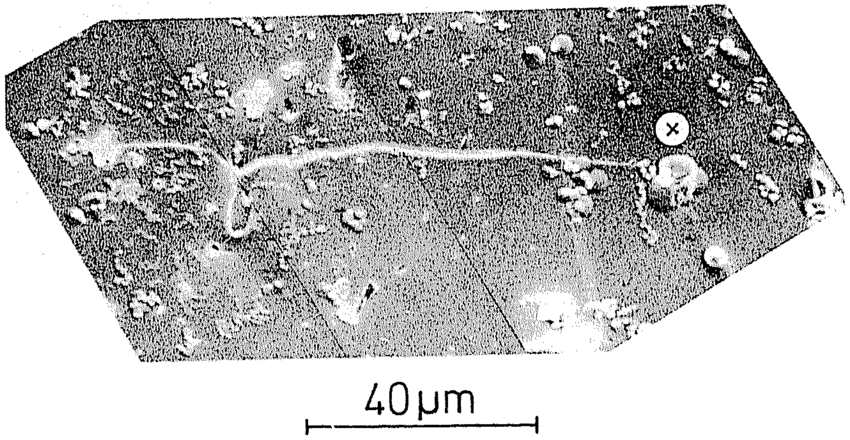

Fig 5 SEM micrograph of a replicated crack retarded at an inclusion (x). The tensile stress axis is vertical

The data on the left in Fig. 4 is for a crack which changed growth mechanism from intergranular (B) to transgranular (C) remote from a triple point. Often with such growth mode changes was a period of zero surface growth, possibly to allow plasticity to be set up in the grain neighbouring the boundary best orientated for slip. The initial transgranular growth was then observed to be by a Mode II opening in a crystallographic manner which then changed to a Mode I opening for Stage II-type transgranular growth. An example of such growth is shown in Fig. 6.

The data on the right in Fig. 4 is for a crack in which plasticity was observed, by interference contrast, to have been built up in a grain neighbouring the boundary; however, a change in growth mechanism did not take place and no crack length increase was observed in over 10^7 cycles.

The greatest disadvantage of any surface observations of contained cracks is that no knowledge can be gained of any sub-surface events; hence, the reason why any grain boundary crack should change growth mode remote from a triple point at any particular point must remain an unknown. It seems likely, however, that some sub-surface disruption of growth, possibly at an inclusion or a triple-point, arrests a crack for a sufficient time for a mature plastic zone to be set up and transgranular growth to occur.

An example, of a crack which had been marked with ink at maximum load and then fatigued to fracture in an effort to look at sub-surface events, is shown in Fig. 7. It can be seen that the crack had a somewhat eccentric shape and this

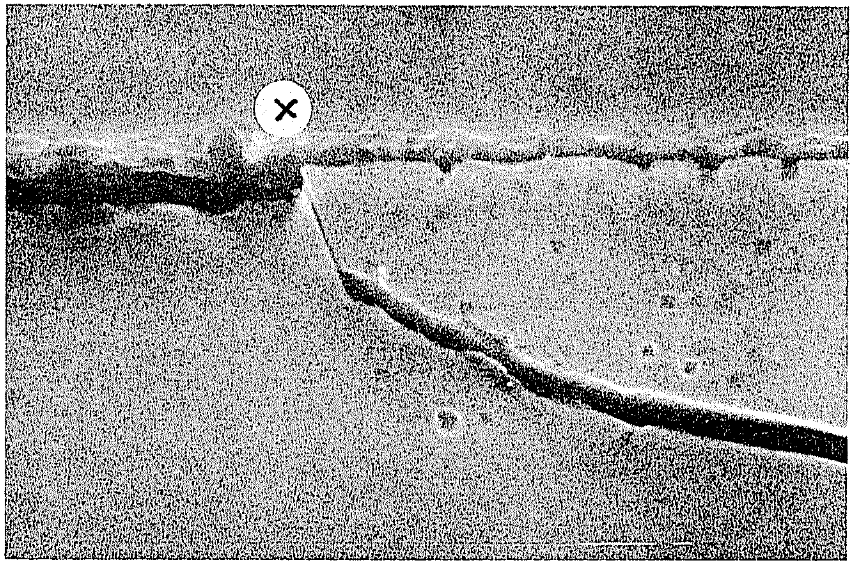

Fig 6 SEM micrograph (at maximum load) of the area in which the growth mechanism changed at X from intergranular to transgranular showing Mode II displacement. The tensile stress is vertical

has been associated with the change in growth mechanism from intergranular to transgranular at a triple point. The intergranular facets were smooth while those in the transgranular growth region were stepped. The non-uniform crack shape also illustrates some of the difficulties of taking propagation rate measurements from surface cracks. One such difficulty is the fact that comparing growth rates using 1/2 surface length c or ΔK relies on cracks having a known shape. In addition to this it would appear from the micrograph that even after a crack tip has passed a triple point on the surface the sub-surface influence of the triple point continues and disrupts the crack shape, thereby changing the surface growth rate.

Conclusions

1. (1) Crack initiation in this peak aged Al 4.5% Cu alloy took place at grain boundaries. TEM examination revealed the presence of preciptate free zones at the boundaries.
2. (2) Growth rates of the cracks were primarily affected by grain boundary triple points. Approximately 50 per cent of such interactions were associated with growth mechanism changes from intergranular to transgranular and 50 per cent were associated with crack deflection when the growth mechanism remained unchanged.

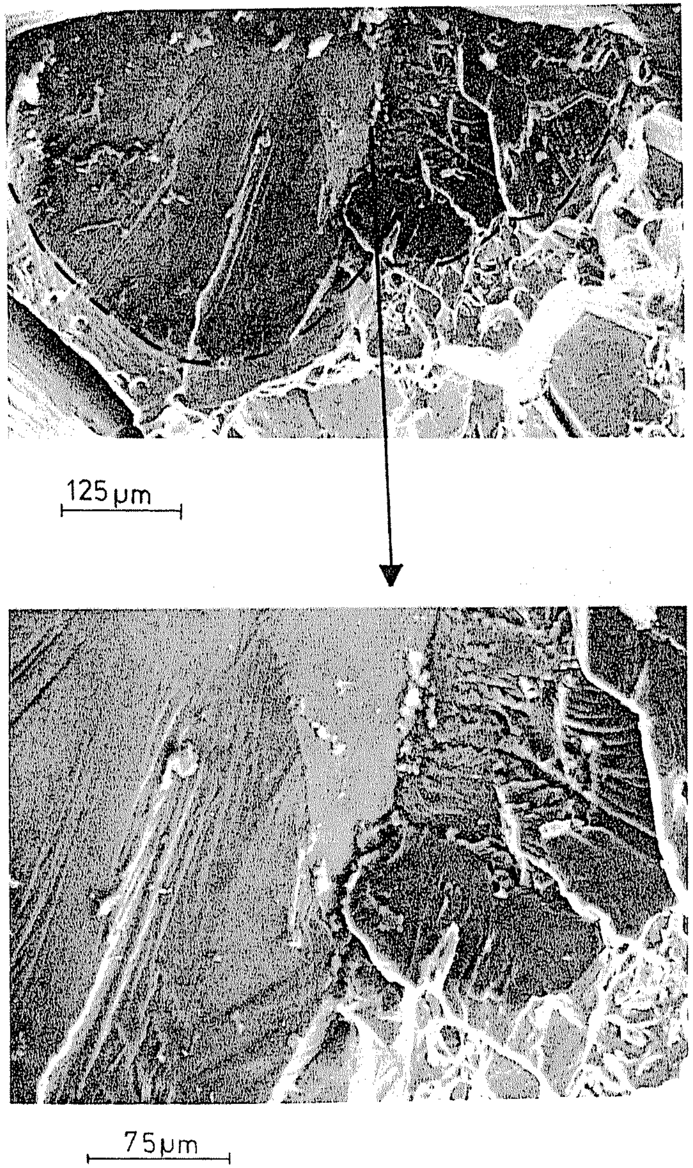

Fig 7 SEM micrographs of the non-uniform crack front associated with an intergranular to transgranular growth mode transition at a triple point

(3) Intergranular growth was also inhibited by inclusions lying on the grain boundaries. Only inclusions greater than 5 μm in diameter had any observable effect on cracks less than 500 μm in length.

(4) Growth mechanism changes remote from triple points were also significant. This type of transition was accompanied by a period of incubation followed by crystallographic transgranular growth with a Mode II opening.

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